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THE EFFECT OF GOLD PLATING ON SOLDERED CONNECTIONS

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S. D. Ebneter

Under the Technical Direction of the
Advanced Methods and Research Section
Electrical Test and Analysis Branch
Analytical Operations Division
Quality and Reliability Assurance Laboratory
George C. Marshall Space Flight Center
Huntsville, Alabama

ABSTRACT

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This report describes an investigation to determine the effects of gold plating on solder connections. A 3 x 3 x 6 factorial experiment was performed and the data were evaluated by an analysis of variance. The thickness of gold plating was shown to have a significant effect on the strength, metallic structure, and visual appearance of the solder connection. Analysis of a study to determine plating-solder, plating-operator, and solder-operator interaction revealed that only solder-operator interaction was significant.

The report concludes that thin layers of gold plating are not detrimental to solder connections. However, tests did not definitely establish that thin layers of gold plating act as a protective coating. Additional testing should be performed to: (a) determine the effectiveness of gold plating in regard to plating thickness, (b) establish limits on process control, and (c) determine possible substitutes for gold plating as a protective coating.

Author

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QUALITY AND RELIABILITY ASSURANCE LABORATORY
RESEARCH AND DEVELOPMENT OPERATIONS

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THE EFFECT OF GOLD PLATING ON SOLDERED CONNECTIONS

SUMMARY

The effect of gold plating thickness on solder connections was investigated by performing a 3 x 3 x 6 factorial experiment and evaluating the data by an analysis of variance. The thickness of gold plating was shown to have a significant effect on the strength, metallic structure, and visual appearance of the solder connection.

It was determined that thin layers of gold are not detrimental to solder connections. However, tests did not definitely establish that thin layers of gold plating act as a protective coating. Test personnel concluded that additional testing should be performed.

A. INTRODUCTION

Gold plating of copper conductor patterns on printed circuit (p-c) boards has been a specification requirement for high reliability equipment for over a decade. The primary reason underlying the gold plating requirement is that it provides a nonoxidizable protective finish which permits the storage of p-c boards over extended time periods. A somewhat weak argument often presented for the use of gold plating is that gold plating increases the solderability of materials.

Several recent investigations have shown that the shear strength of gold-in-solder alloys is reduced considerably as the percent of gold-to-solder is increased and that the wettability of gold plated copper surfaces is inferior to unplated copper. These results were further investigated in a factorial experiment to determine the effects of gold plating and the validity of present specification requirements. This report is based on this investigation.

B. GOLD PLATING

The primary function of gold plating over copper printed circuit surfaces is to protect the copper from atmospheric contaminants and the formation of oxides. Gold is well suited for this application, from the standpoint of oxidation prevention, since it is the lowest in the electromotive series. However, gold plating is porous, and if not applied in sufficient thickness, complete protection of the copper surface is not accomplished.

The degree of porosity determines the effectiveness of the gold plating in preventing corrosive gases and materials from coming into contact with the base metal. Pores are essentially microchannels or macrochannels extending from the surface of the deposit to the base metal. Micropores are primarily due to the structural characteristics of the electrodeposit which is a function of the plating process parameters, electrolyte, electrodes, deposition rates, etc. This is known as intrinsic porosity, and it is always present. Macropores are commonly referred to as accidental (or gross) porosity and are due mainly to the inclusion of foreign matter. Porosity in the form of channels can also be found due to the occurrence of internal stresses which lead to cracking of the plating.

Plated metals exhibit a definite grain structure and size. Grain size is the most important factor in determining the required thickness of a given plating material used to prevent corrosive attack of the base metal. For each size of grain there is a minimum amount of plating required to provide a pore-free surface. Coarser grain platings require thicker coatings to eliminate intrinsic porosity.

The amount of gold required to provide a pore-free surface varies with the type of bath (cyanide or acid); generally, the cyanide gold requires a thicker plating. Estimates for effective acid gold plating range from 30 microinches to 230 microinches.

The gold plating process is difficult to control under mass production conditions which result in a wide variation of plating thicknesses. Plating thicknesses vary from the center of the p-c board to the edges, often as much as 94 microinches, due to the various current densities of the plating bath. In addition, variation in the gold content and pH of the bath change the plating time requirements which are at best only indicative of final plating thickness. Thus, a plating thickness specified as 100 microinches was measured as approximately 250 microinches.

When tin-lead solder is used to form a metallic conducting junction with a base metal, normally copper for p-c board applications, and a plating of gold is deposited over the junction, the gold plating goes into solution and is dispersed throughout the solder matrix. This alloying of the gold with solder reduces the wetting action and increases the porosity and brittleness of the joint. When this occurs it is usually evidenced visually by a rough, coarse, dull appearance of the solder joint.

F. Gordon Foster studied the effects of gold on solder and its constituents with both binary and ternary alloys of tin, lead, and gold. His investigation concluded that gold will embrittle the solder if present in amounts greater than 5 percent by weight and that a small amount of gold may not be undesirable in many types of joints.[1]

J. D. Keller studied the problem from the standpoint of spreading and wettability of solder and determined that it is desirable to eliminate gold plating. Solder spread tests of 60-40 tin-lead solder on gold plated copper exhibited limited spread area and high dihedral angle of wetting, whereas solder spread tests on hot-tin dipped boards showed that the spread area was more than doubled and the dihedral angle of wetting was reduced to approximately zero.[2]

1 Refer to Item 2 of the Bibliography.
2 Refer to Item 3 of the Bibliography.

To correlate these findings with Marshall Space Flight Center specification requirements, a statistically designed experiment was conducted.

C. STATISTICAL MODEL OF EXPERIMENT

The statistical model for this experiment was an analysis of variance, three-way classification (3 x 3 x 6), fixed constant model with three measurements per cubical. The model is shown in Figure 1.

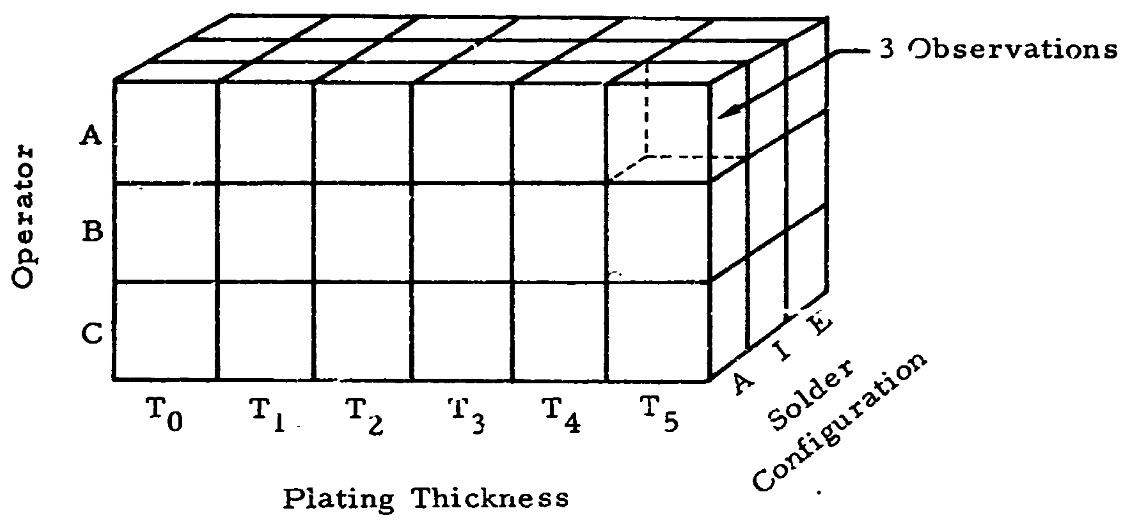


Figure 1. Statistical Model

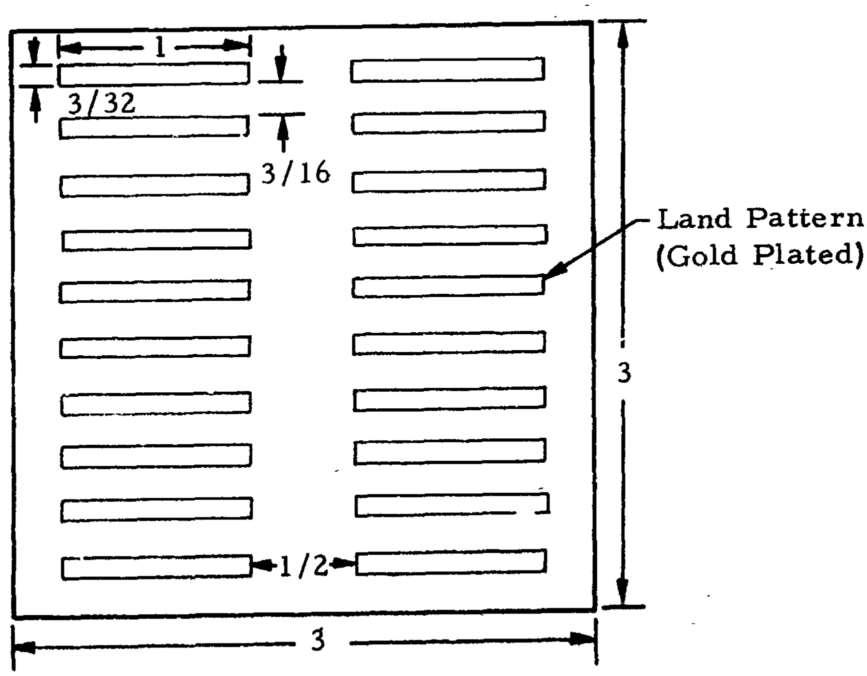
Three operators, designated A, B, and C, were selected for their soldering experience. Operator A was an experienced fabrication technician trained at the NASA Soldering School. Operator B was recently trained at the NASA school but had no fabrication experience. Operator C was a NASA Soldering School instructor.

Solder connections were made in three different configurations with regard to the amount of solder employed: acceptable (A), excess (E), and insufficient (I) as interpreted from MSFC-PROC-158B, NPC 200-4, and MSFC inspection criteria.

The third classification, plating thickness, consisted of six levels designated T_0 through T_5 which are discussed in the following paragraphs.

D. TEST SAMPLES

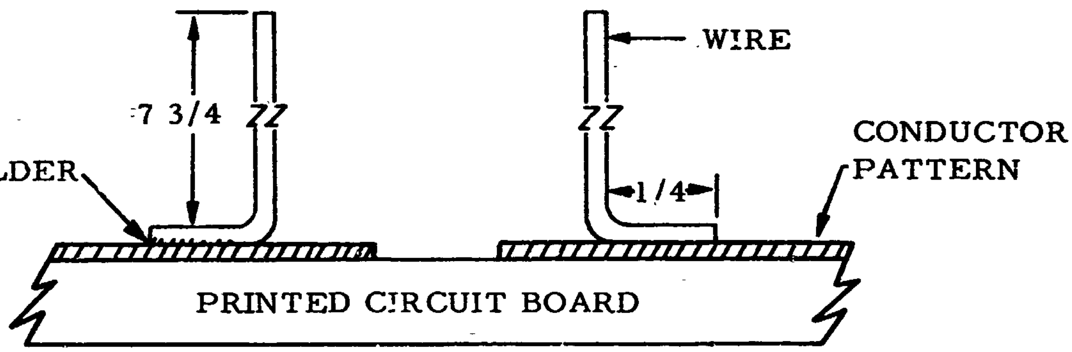
The test samples were 2-ounce copper clad printed circuit boards with a land pattern identical to that specified by paragraph 5.14.1 of MSFC-STD-154 and are shown in Figure 2. The boards were gold plated by the acid gold plating process in a production plating shop. Plating thicknesses varied so greatly, even from strip to strip on the same board, that three measurements by the beta-ray backscatter principle were made on each strip of each board to increase the reliability of the measurements. From the overall measurement results, plating thicknesses of T_0 (no gold), T_1 (45 ± 5 microinches), T_2 (85 ± 5 microinches), T_3 (155 ± 5 microinches), T_4 (210 ± 5 microinches), and T_5 (255 ± 5 microinches) were selected for the experiment. Twenty-seven strips of each plating thickness were selected for evaluation.



NOTE: ALL DIMENSIONS ARE IN INCHES

Figure 2. Test Board Configuration

Tinned copper bus wire, No. 22 AWG of the configuration shown in Figure 3 was soldered to each of the selected strips in accordance with MSFC-PROC-158B using 60-40 tin-lead solder. Three operators designated A, B, and C were employed in the soldering and each was instructed to solder nine connections to each plating thickness (T_0 through T_5).



NOTE: ALL DIMENSIONS ARE IN INCHES

Figure 3. Test Item Configuration

For each thickness, three connections were to be soldered using the proper amount of solder, three using an insufficient amount of solder, and the remaining three using an excessive amount of solder. Acceptable, insufficient, and excess amounts were interpreted by each operator from MSFC-PROC-158B.

E. TEST PROCEDURE

The test specimens were mounted in a Dillon Model M universal tester and "pull-tested" to destruction. The loading was normal to the soldered wire, (Figure 4) and applied at a crosshead rate of 0.5 inch per minute.

The load required to destroy the soldered connection and the mode of failure were observed and recorded. Failure modes were designated as shear, peel, and peel-shear referring to the manner in which the connection failed. A shear failure mode is one in which the

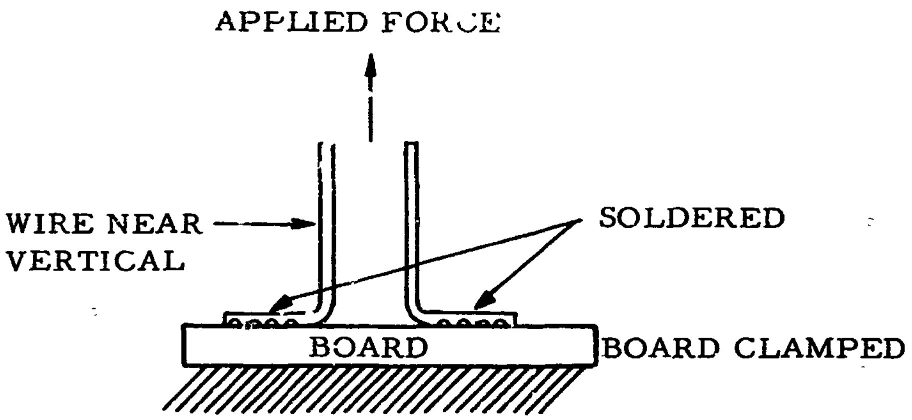


Figure 4. Method of "Pull Test"

wire, under load, shears through the applied solder mass. A peel failure mode is one in which the entire mass of solder and wire, under sufficient loading, peels from the copper surface. These are depicted in Figure 5. A peel-shear mode is one in which both of the above failure modes are evident to some degree.

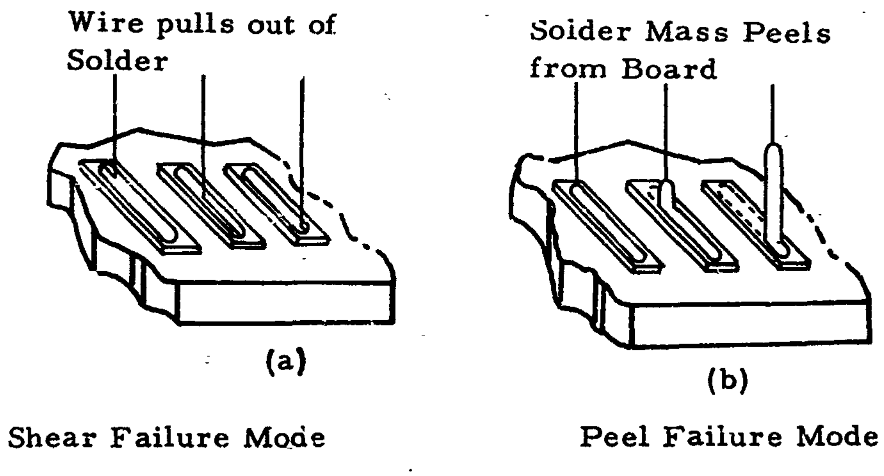


Figure 5. Failure Modes

F. DATA ANALYSIS

The data accumulated are presented in Chart 1. Each cubical has three quantitative values of pull strength. The figure in the lower right corner of each cubical represents the cell total. An analysis of variance of the data was performed; the results are depicted in Table 1.

The error term used for testing the main and two-way interaction effects includes the three-way interaction. Comparison of calculated "F" values with those obtained from an "F" table shows that several effects are significant.[3]

All of the main effects, plating thickness, solder configuration, and operator, were significant at both 5 percent and 1 percent levels. The solder configuration and operator effects were highly significant.

Further analysis of the gold plating thickness was performed by application of Duncan's multiple range test at the 5-percent significance level. The results are shown in Figure 6. The average strength ($\bar{T}$) of the pull tested solder connections for each gold plating thickness level (T_0 through T_5) is arranged in ascending order, from lowest to highest. If a bar connects two or more of the levels, then these levels are not significantly different between themselves, but they are significantly different from the other levels. Thus from Figure 6, there is no significant difference between T_0, T_1, and T_2, nor is there a significant difference between the strength of solder joints made to unplated clean copper surfaces and those made to relatively thin gold plated surfaces. However, there is a significant difference between the strength of joints made at lower plating thicknesses and those made at higher thicknesses.

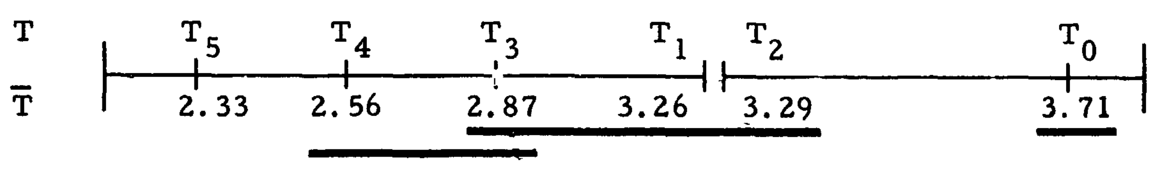


Figure 6. Results of Duncan's Multiple Range Test

Visual inspection of the soldered connections reveals a successive degradation in the appearance of the solder with successive increase in gold plating thickness. Photographs of typical solder connections at each

3 The ratio of two variances possesses an F distribution. In this case, the F distribution is for the ratio of an effect variance to the error variance. Thus, the F distribution is used as a statistical test.

	OPERATOR A			OPERATOR B			OPERATOR C			
	SOLDER CONFIGURATION			SOLDER CONFIGURATION			SOLDER CONFIGURATION			
	A	I	E	A	I	E	A	I	E	
T_C (No Gold)	3.25 3.63 3.75 10.63	3.62 2.50 2.87 8.99	3.87 2.5 4.63 11.00	5.25 2.00 3.94 11.19	1.87 2.87 2.87 7.61	7.12 4.12 3.87 15.11	4.81 5.31 2.62 12.74	2.5 2.37 1.75 6.62	8.31 3.5 4.37 16.18	100.07 n_r = 27
T_1 (45 ± 5 μ in.)	2.87 2.94 2.25 8.06	2.00 1.50 2.25 5.75	2.63 3.37 3.5 9.50	3.00 2.50 2.87 8.37	1.87 3.25 4.81 9.93	4.0 3.5 2.87 10.37	3.37 4.0 3.62 10.99	3.87 2.37 2.5 8.74	4.31 6.31 5.87 16.49	88.20
T_2 (85 ± 5 μ in.)	2.31 2.62 2.00 6.93	2.12 1.50 2.00 5.62	2.87 2.87 2.50 8.24	2.25 3.00 4.50 9.75	1.87 4.56 2.25 8.68	4.0 3.87 3.37 10.74	3.18 3.81 3.87 10.86	2.69 3.5 1.18 7.37	7.62 5.62 7.31 20.55	88.74
T_3 (155 ± 5 μ in.)	3.18 2.18 1.56 6.92	3.50 0.50 0.75 4.75	4.13 1.75 3.25 9.13	2.0 3.13 3.50 8.63	0.56 1.00 3.94 5.5	4.25 3.94 4.5 12.69	3.87 3.56 2.5 9.93	2.43 0.5 1.62 4.55	4.0 4.69 6.87 15.56	77.66
T_4 (210 ± 5 μ in.)	1.25 1.62 1.88 4.75	1.375 0.75 1.13 3.25	2.25 3.25 1.87 7.37	2.25 2.50 1.37 6.12	4.31 3.00 1.56 8.87	2.5 4.0 2.13 8.63	3.5 4.0 1.06 8.56	1.81 1.25 1.87 4.93	7.75 5.25 3.75 16.75	69.23
T_5 (255 ± 5 μ in.)	1.37 1.87 1.25 4.49	1.63 1.56 1.75 4.94	3.25 1.25 1.81 6.31	1.50 2.25 0.63 4.38	1.75 2.5 0.87 5.12	2.25 2.25 2.25 6.75	3.37 3.0 2.5 8.87	1.0 0.62 1.5 3.12	5.06 7.5 6.5 19.06	63.04
	41.78 n_c = 18	33.3	51.55	48.44	45.71	64.29	61.95	35.33	104.59	486.94 N = 162

Note: Cell Entries are Pull Test Strength in Pounds

n_c = number samples per column
n_r = number samples per row
N = Total number of samples

Chart 1. Test Results

Table 1. Analysis of Variance

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F_{test}	$F_{.95}$ (table)	$F_{.99}$ (table)	Sig.
Plating Thickness	5	35.0932	7.016	7.0214	2.29	3.17	Yes
Solder Configuration	2	107.0718	53.5359	53.5573	3.07	4.79	Yes
Operator	2	52.8339	26.4169	26.4274	3.07	4.79	Yes
Plating-Solder Interaction	10	6.3394	0.6339	0.6341	1.91	2.47	No
Plating-Operator Interaction	10	9.9435	0.9943	0.9946	1.91	2.47	No
Solder-Operator Interaction	4	49.0034	12.2508	12.2557	2.45	3.48	Yes
Error	128	127.9570	0.9996				
Totals	161	388.2422					

Note: When F_{test} is greater than $F_{.95}$ or $F_{.99}$ there is a significant difference at the 95% or 99% significance level, respectively.

gold plating thickness level are shown in Figures 7 through 12. Solder connections shown in Figures 7, 8, and 9 are bright and shiny, and exhibit the characteristics of a properly executed solder connection. The connection shown in Figure 9 (83 microinches gold), although rated as acceptable, appears somewhat duller and the structure is slightly coarser. The solder connections illustrated in Figures 10, 11, and 12 are unacceptable and exhibit extreme coarseness of grain, porosity, and dullness. Plating thickness T_3 appears to be the approximate level where gold plating becomes extremely detrimental. The cross-sectioned sample exhibits porosity and needle-like grains corresponding directly with the statistical findings which showed that thicker platings are significantly different from the thinner platings.

Metallographic examination of solder samples used in the experiment revealed a direct correlation between visual exterior inspection results, statistical analysis results, and the interior of the solder joint. Figures 13 through 24 are photomicrographs (100x) of the cross-sectioned samples. These cross sections reveal that platings of T_0, T_1, and T_2 (0, 45, and 88 microinches) do not exhibit porosity. However, these solder connections made on T_3, T_4, and T_5 (plating thicknesses of 149, 205, and 250 microinches) are extremely porous. These correlate directly with visual inspection of the joints (see Figures 7 through 12) and with the conclusions drawn from the statistical analysis of variance.

Further metallurgical analysis was performed at a higher power to observe the grain structure. The analysis revealed the existence of large, white, acicular crystals dispersed throughout the matrix. None of these crystals are evident in those joints which were made on unplated copper surfaces. At T_1 and T_2, a minute amount of these crystals appeared as shown in Figures 16 and 18. The frequency of occurrence and the size of these crystals increase with the thickness of gold plating as can be evidenced from observation of Figures 14 through 24. Once again, a significant amount of sizable, white, acicular crystals appeared at thickness T_3 (149 microinches). These needle-like crystals are very similar to those reported by F. Gordon Foster[4] in a ten percent gold-in-tin alloy, thus lending support to the theory that they are a gold-in-tin alloy.

The solder configuration effect was highly significant, which indicates that the amount of solder applied to the joint has a significant effect on the strength of the solder connection. The excessive solder

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4 Refer to Item 2 of the Bibliography.

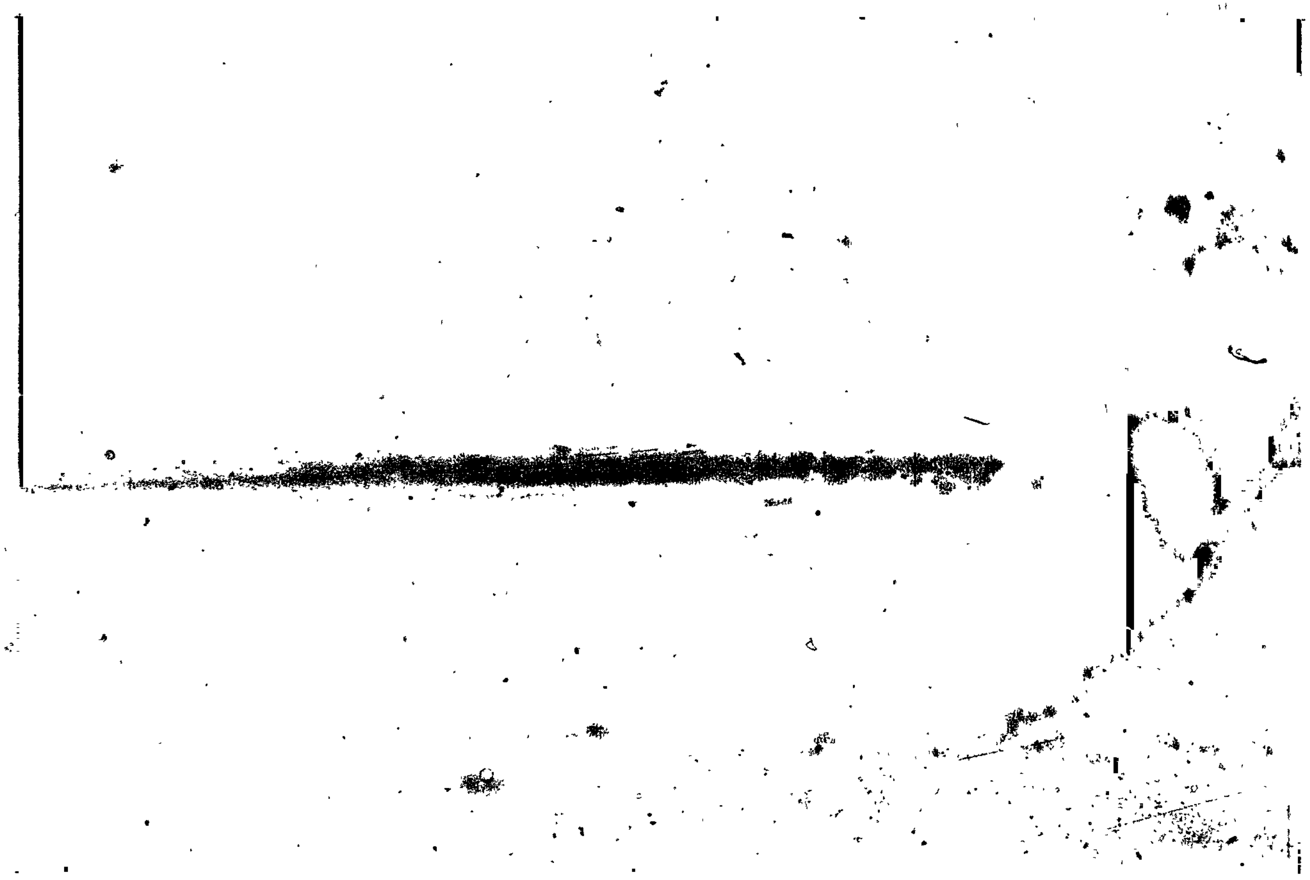

Figure 7. Solder Connection Over Plating T_0 (No Gold)

Figure 8. Solder Connection Over Plating T_1 (45 Microinches Gold)

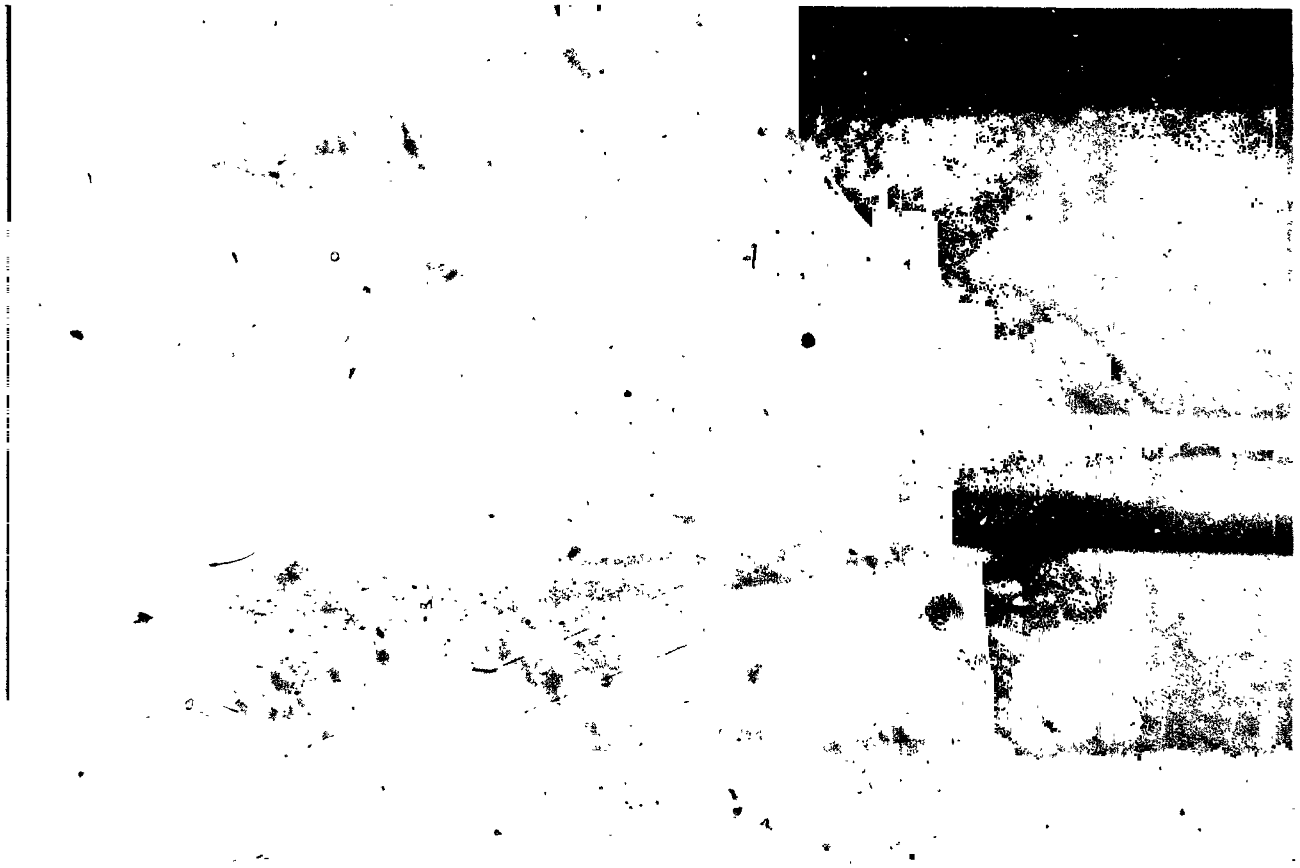

Figure 9. Solder Connection Over Plating T_2 (83 Microinches Gold)

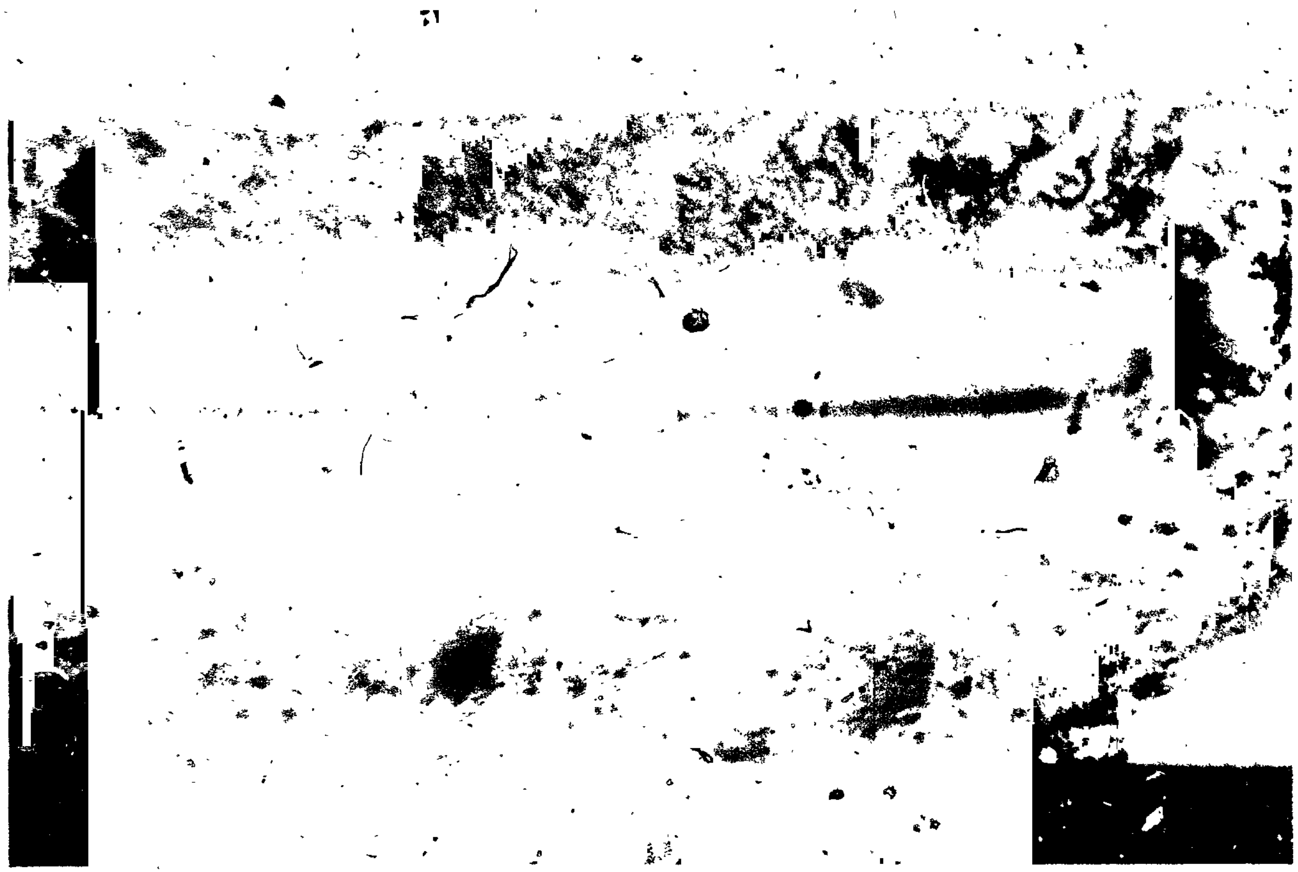

Figure 10. Solder Connection Over Plating T_3 (153 Microinches Gold)

Figure 11. Solder Connection Over Plating T_4 (206 Microinches Gold)

Figure 12. Solder Connection Over Plating T_5 (245 Microinches Gold)

Figure 13. Magnification 100x Gold Plating - T_0 (No Gold)

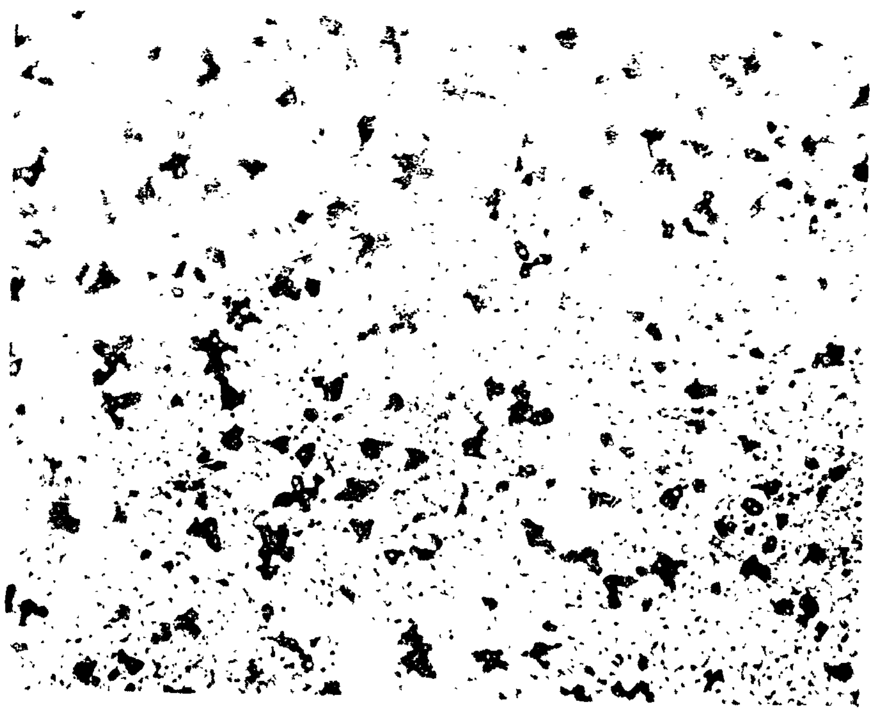

Figure 14. Magnification 500x Etchant $FeCl_3$ Gold Plating - T_0 (No Gold)

Figure 15. Magnification 100x Gold Plating - T_1 (45 Microinches Gold)

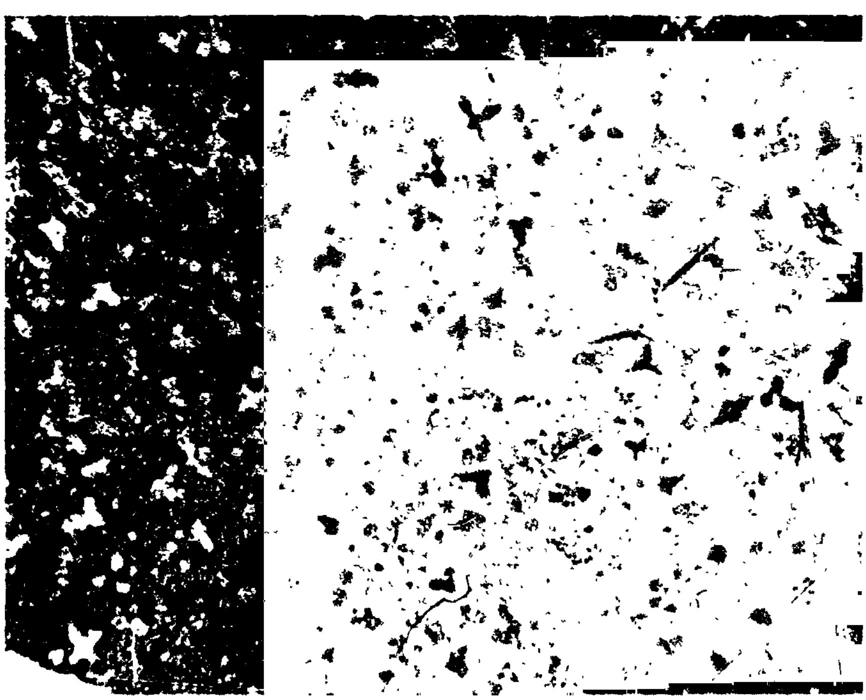

Figure 16. Magnification 500x Etchant $FeCl_3$ Gold Plating - T_1 (45 Microinches Gold)

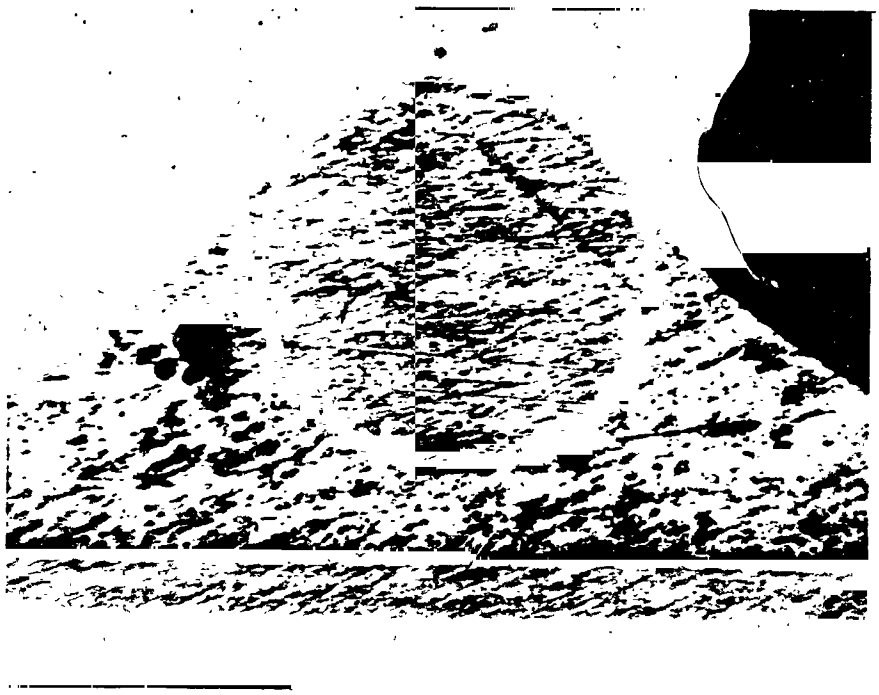

Figure 17. Magnification 100x Gold Plating - T_2 (88 Microinches Gold)

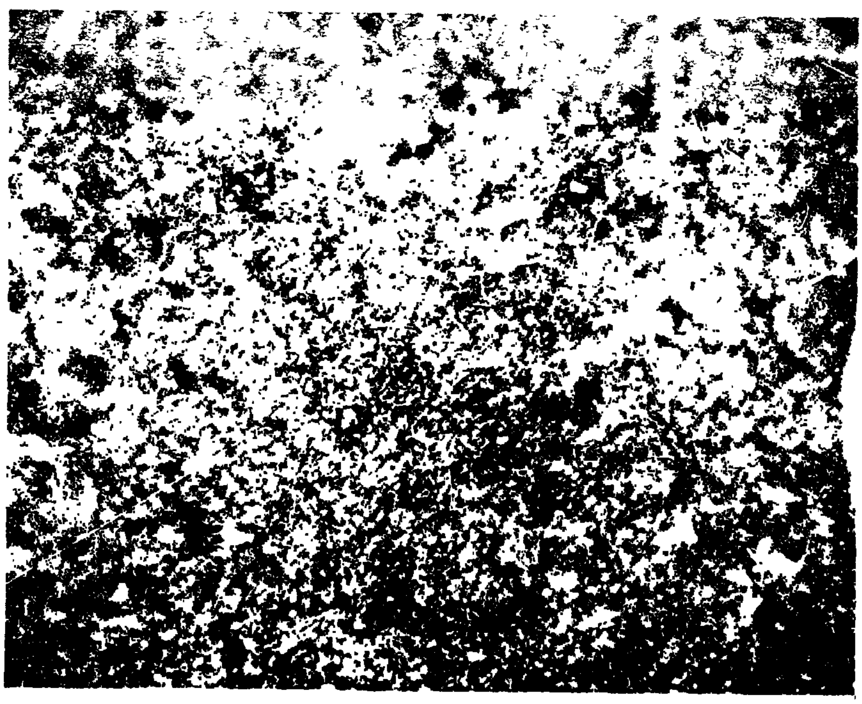

Figure 18. Magnification 500x Etchant $FeCl_3$ Gold Plating - T_2 (88 Microinches Gold)

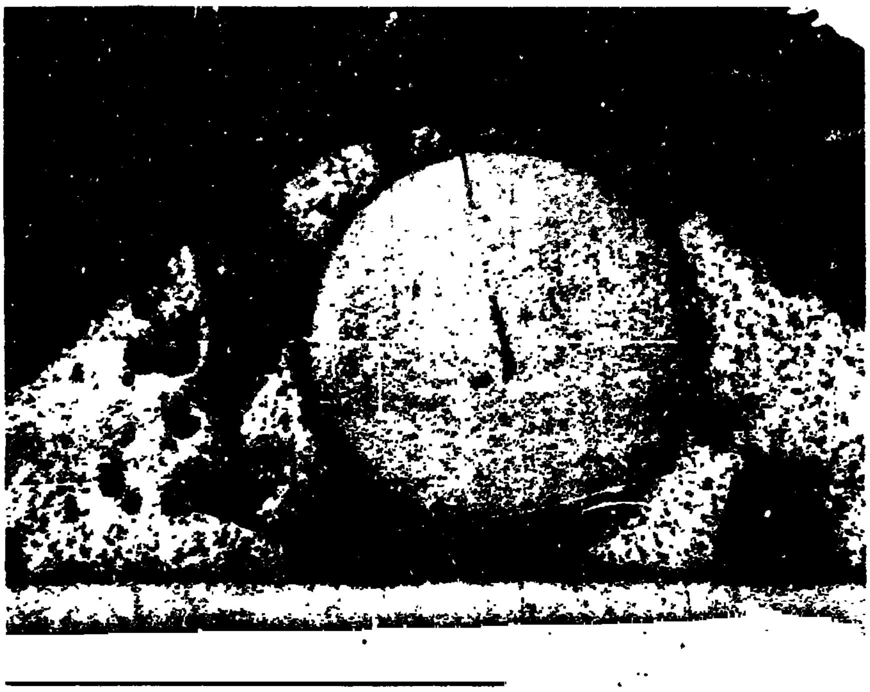

Figure 19. Magnification 100x Gold Plating - T_3 (149 Microinches Gold)

Figure 20. Magnification 500x Etchant $FeCl_3$ Gold Plating - T_2 (149 Micro-inches Gold)

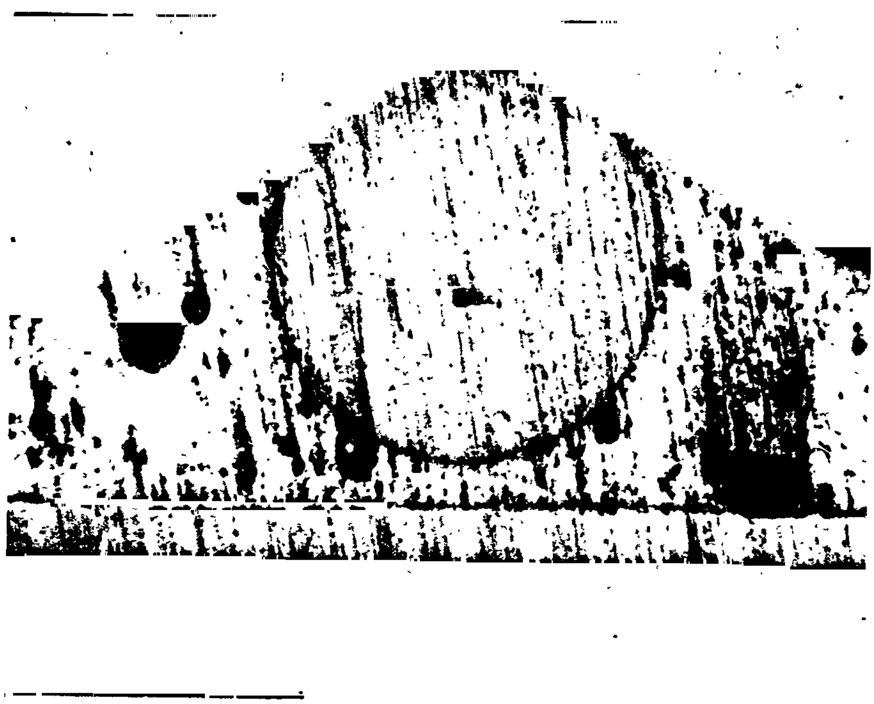

Figure 21. Magnification 100x Gold Plating - T_4 (205 Microinches Gold)

Figure 22. Magnification 500x Etchant $FeCl_3$ Gold Plating - T_4 (205 Micro-inches Gold)

Figure 23. Magnification 100x Gold Plating - T_5 (250 Microinches Gold)

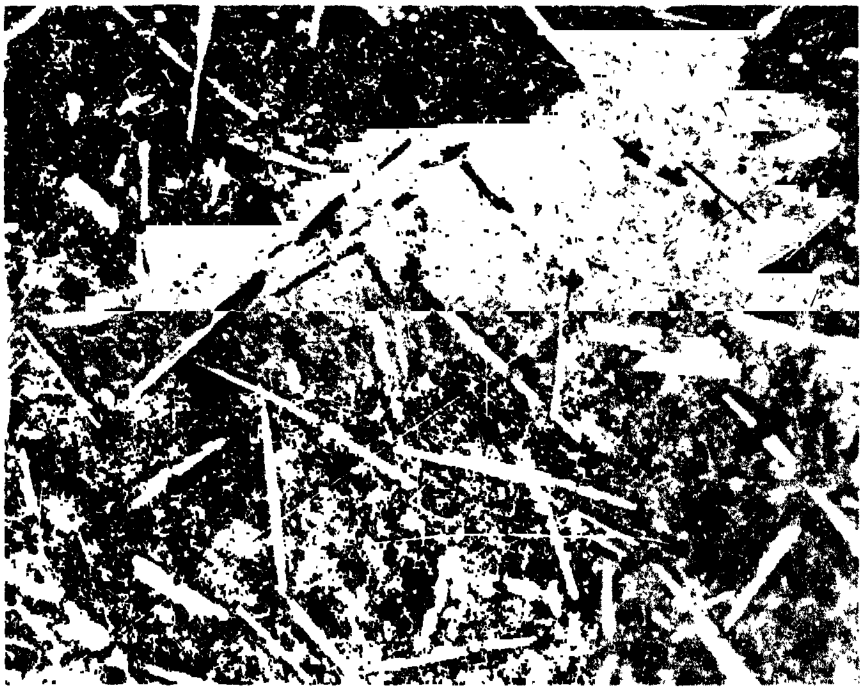

Figure 24. Magnification 500x Etchant $FeCl_3$ Gold Plating - T_5 (250 Micro-inches Gold)

configuration definitely showed a higher joint strength at all levels. This becomes a significant factor in soldering to a gold plated surface since, according to Foster's results, the joint is embrittled when gold is present in amounts greater than 5 percent.

To support this contention for production work, calculations were made to determine what thicknesses corresponded to certain gold-tin percentages. Table 2 presents the results of these calculations.

Table 2. Calculated Percent Gold by Weight

Plating Thickness (microinches)	Weight of Gold (grams)	% Gold to Solder Insufficient Solder	% Gold to Solder Proper Amount	% Gold to Solder Excess Solder
0	0	0	0	0
45	5.00×10^{-4}	4.1	1.72	1.06
85	9.45×10^{-4}	7.8	3.25	2.01
155	17.23×10^{-4}	14.3	5.91	3.66
210	23.35×10^{-4}	19.1	8.02	4.96
255	28.35×10^{-4}	23.3	9.74	6.01

NOTES:

Average weight of Insufficient Solder Joint (of configuration used in this experiment) - 121.9×10^{-4} grams

Average weight of Proper Solder Joint (of configuration used in this experiment) - 291.3×10^{-4} grams

Average weight of excess solder joint (of configuration used in this experiment) - 470.4×10^{-4} grams

For an acceptable joint at a plating thickness of 155 microinches, the gold-solder percentage is approximately 5.91 percent. At levels T_0, T_1, and T_2 the percentage is considerably less than 5 percent. This corresponds with the results of the analysis of variance, visual inspection, and metallographic examination. With thicker gold plating it becomes very easy to exceed the 5 percent level when insufficient solder is used.

The two-way interaction effects are shown in Figures 25, 26, and 27. From the analysis of variance table (Table 1) the plating-solder and plating-operator interactions were not significant; however, the solder-operator interaction was significant.

On Figure 25, note that a definite gap exists between the plots which indicates a sizable effect due to the amount of solder used. This is as it should be, since the main effect of solder configuration was found to be significant (see Table 1). Observe that the plots are not parallel indicating that there is some interaction present, although it

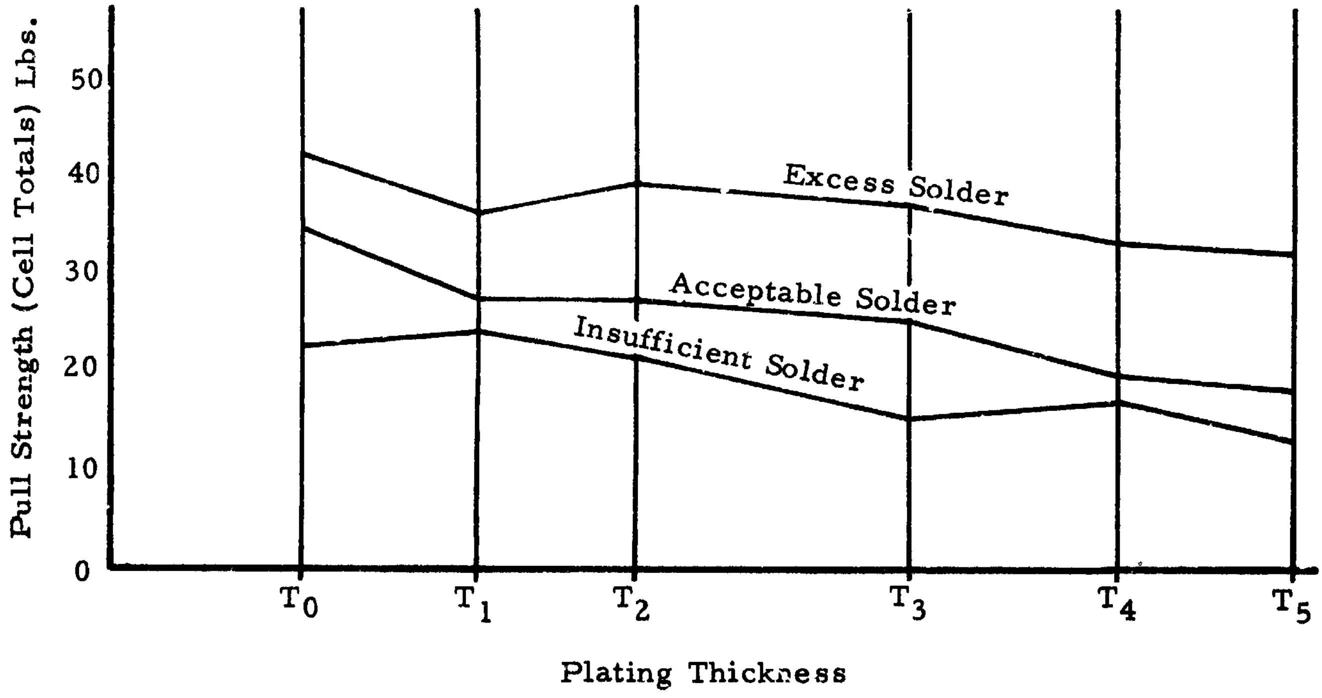

Figure 25. Plating-Solder Interaction

is not significant. In addition, a definite linear trend of reduced joint strength with increased plating thickness exists.

Virtually the same observation can be made with regard to Figure 26. Note in this figure that operator A and operator B plots are almost parallel. However, operator C deviates considerably indicating that operator C has introduced the major part of the interaction between the plating thickness and operator variables. This is further substantiated by Figure 27 which shows the solder-operator interaction.

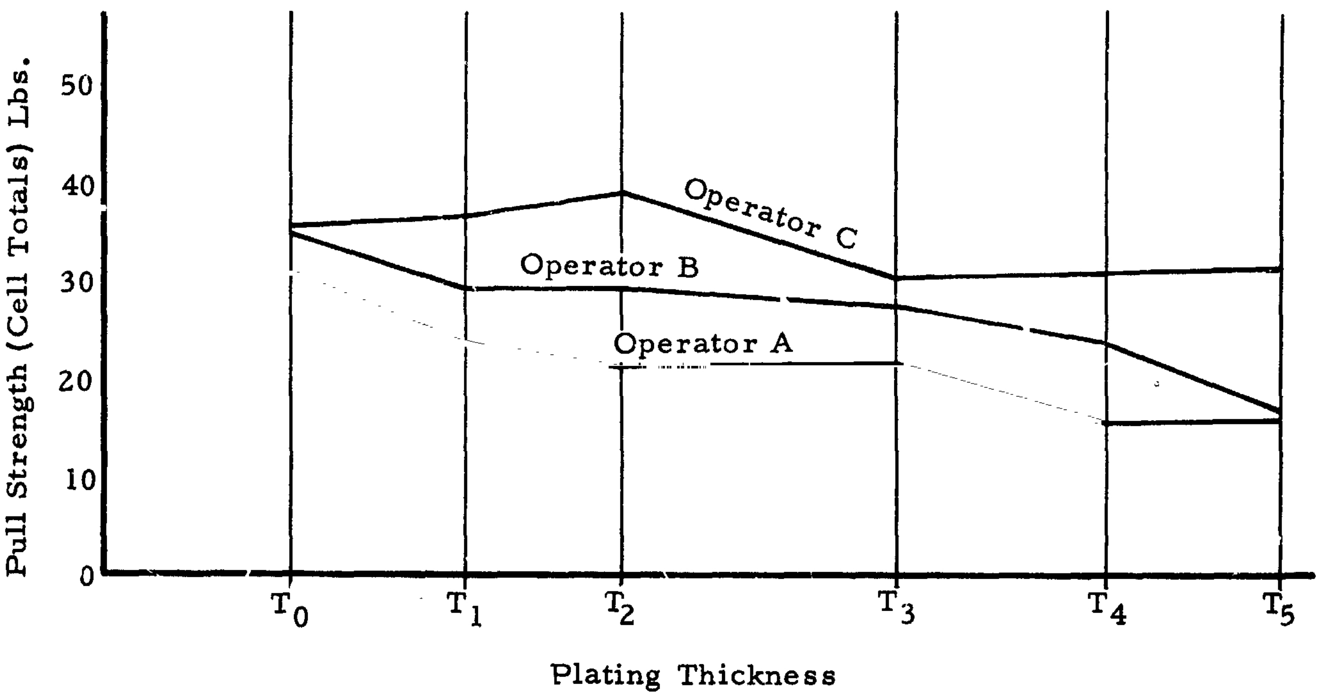

Figure 26. Plating-Operator Interaction

The mode of failure - peel, shear, or peel-shear - was noted during the pull testing of the soldered connections. The results are shown in Chart 2 and Figure 28. Note that for all solder-over-gold

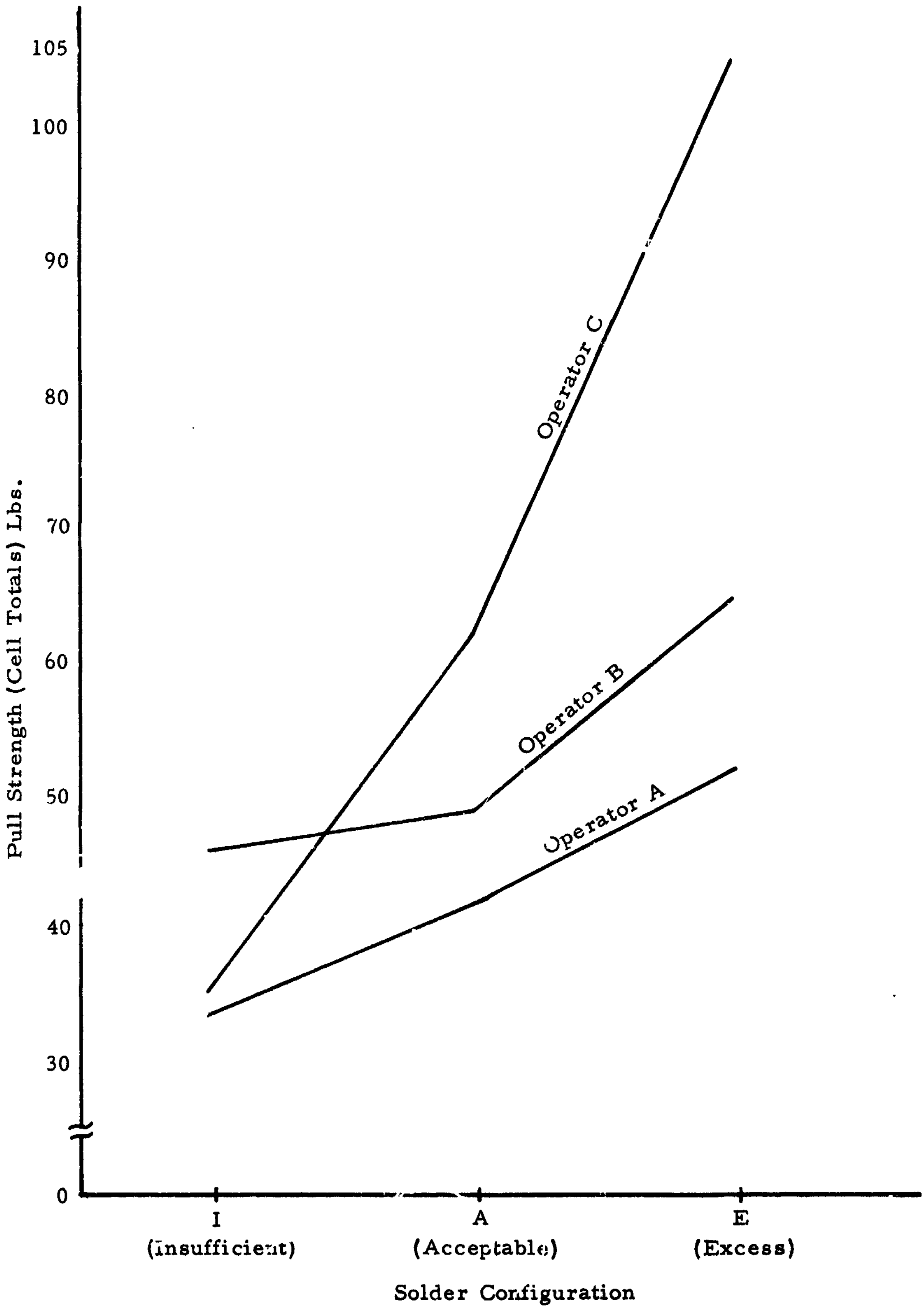

Figure 27. Solder-Operator Interaction

Failure Mode	T_0			T_1			T_2			T_3			T_4			T_5			
	A	I	E	A	I	E	A	I	E	A	I	E	A	I	E	A	I	E	
Peel	0	0	0	4	6	1	5	6	1	4	7	0	3	6	3	5	8	4	63
Shear	8	9	9	1	1	7	1	2	8	0	2	3	0	0	1	0	0	2	54
Peel Shear	1	0	0	4	2	1	3	1	0	5	0	6	6	3	5	4	1	3	45
																			162

Chart 2. Failure Mode Data

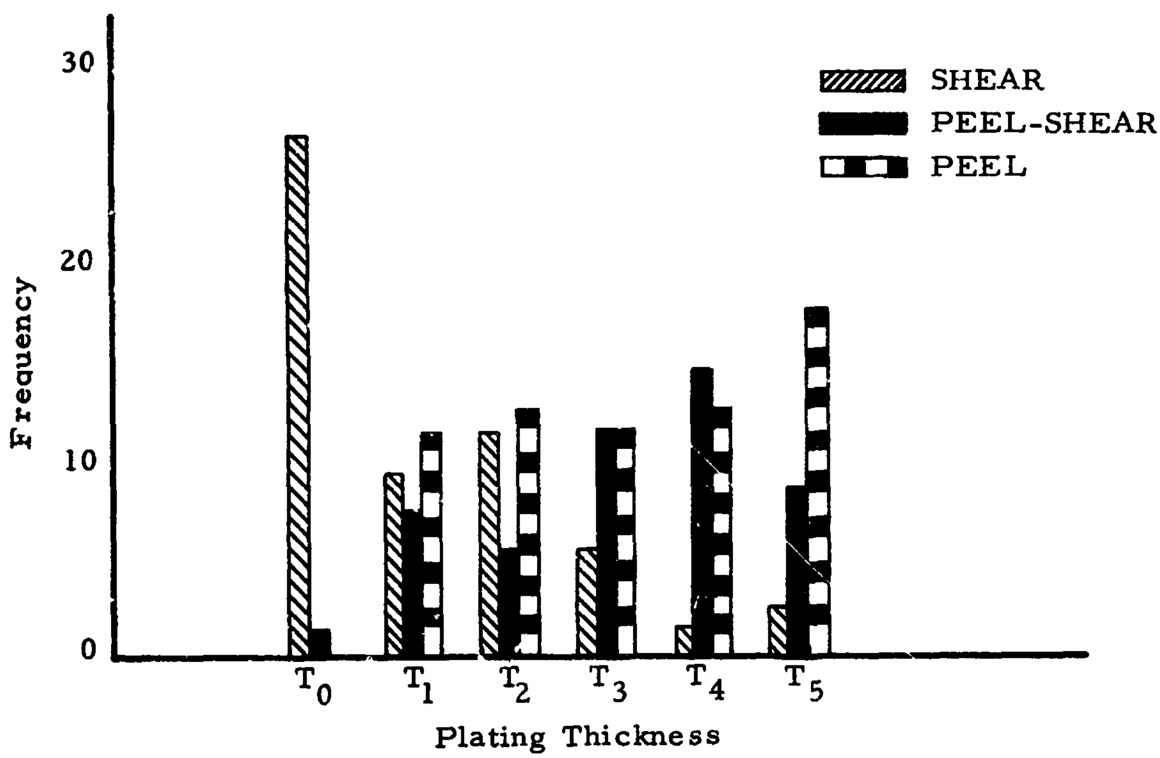

Figure 28. Failure Distributions

connections a significant number failed under loading in a peel mode, while none of the connections on solder-over-unplated surfaces (T_0) failed in a peel mode. Thus, an inferior intermetallic bond is produced at the copper-solder interface when the copper is gold plated.

The failure mode data indicates that the requirement imposed by paragraph 5.14.1 of MSFC-STD-154 cannot be met by a gold plated p-c board if the solder connections are made in accordance with MSFC-PROC-158B.

G. CONCLUSIONS

Based on the results of this experiment, the following conclusions were reached.

1. The strength of solder connections made over relatively thin gold plating (i.e., connections in which the gold-to-solder percentage is less than 6 percent) is greater than solder connections made over thicker platings. This conclusion is in direct agreement with Foster's conclusion that a small amount of gold may not be detrimental to the solder joint.

2. There is a distinct trend toward porosity and reduced strength of solder-over-gold connections as the plating thickness is increased.

3 The operator's interpretation of the specification requirements plays a significant role in the strength of the soldered connections.

4. Test results indicate that the gold plating requirements of MSFC-STD-154 (paragraph 5.14 and subparagraphs) cannot be met if the plating is of sufficient thickness to perform its intended function as a protective coating.

The following are important factors when considering gold plating.

1. The extremely high cost of gold.

2. Removal of the gold by hand erasing prior to soldering requires from approximately 1 minute (50 microinches) to approximately 3 minutes (250 microinches) which can contribute considerable to manufacturing costs.

3. Problems in controlling the gold plating system to achieve a specified thickness of gold plating.

The general conclusion is that thin layers of gold plating do not appear to be detrimental to solder connections. However, tests did not definitely establish that thin layers of gold perform the intended function of a protective coating. The probability of obtaining excessively thick platings is high because of poor process control. Therefore, additional testing should be performed to determine: (a) the effectiveness of gold plating as a protective coating as a function of thickness, (b) limits on process control, and (c) possible substitutes for gold plating as a protective coating.

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THE EFFECT OF GOLD PLATING
ON SOLDERED CONNECTIONS

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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